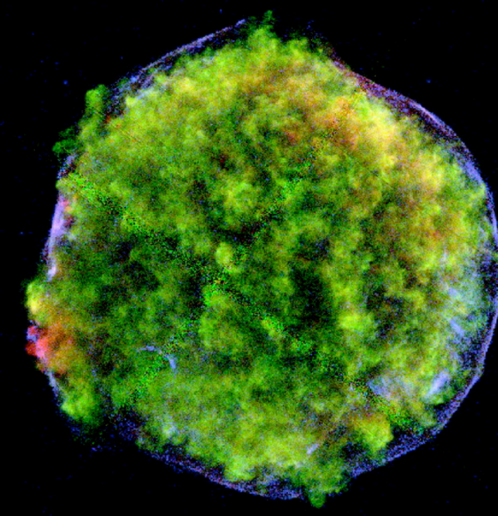
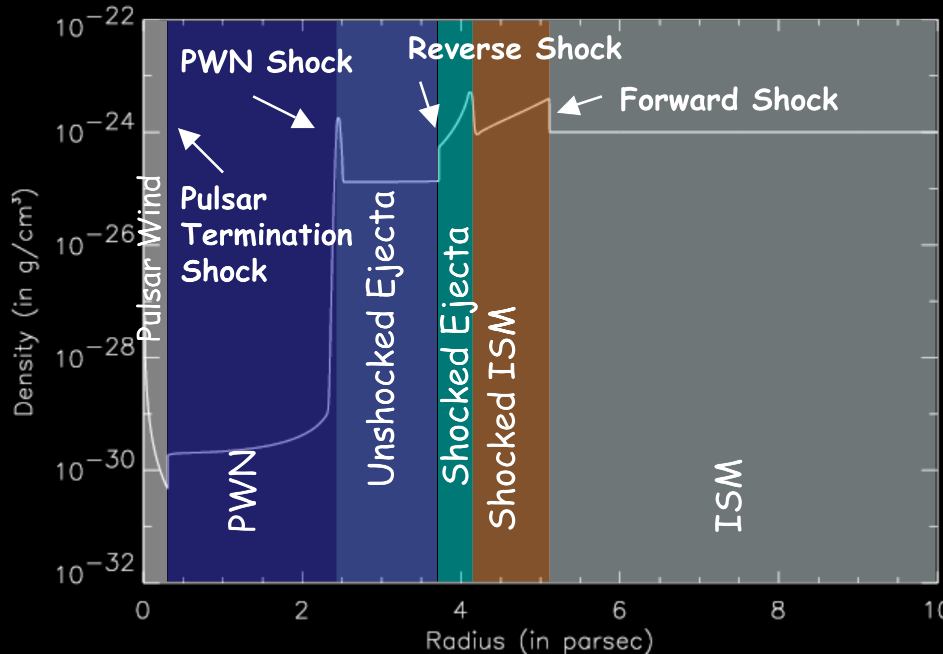
VHE γ-rays from

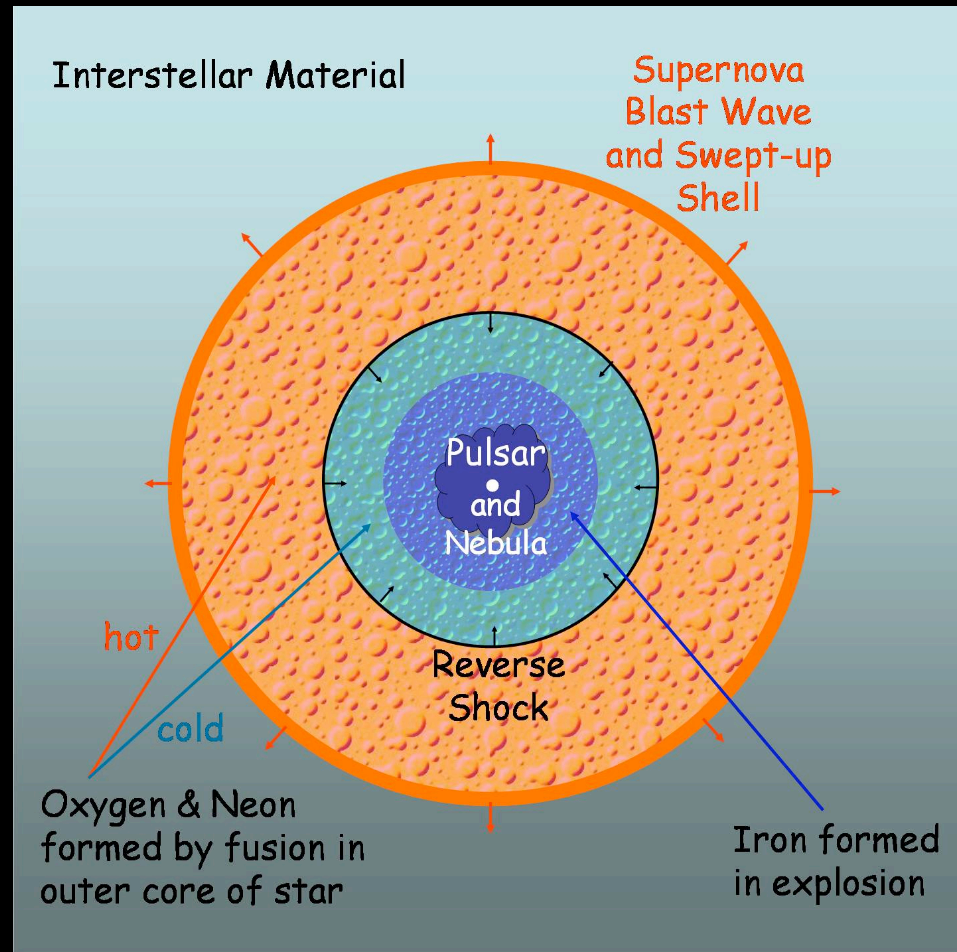


Supernova Remnants

Patrick Slane (CfA)

SNRs: The (very) Basic Structure





- **Pulsar Wind**
  - sweeps up ejecta; shock decelerates flow, accelerates particles; PWN forms
- **Supernova Remnant**
  - sweeps up ISM; reverse shock heats ejecta; ultimately compresses PWN; particles accelerated at forward shock generate turbulence; other particles scatter from waves and receive additional acceleration

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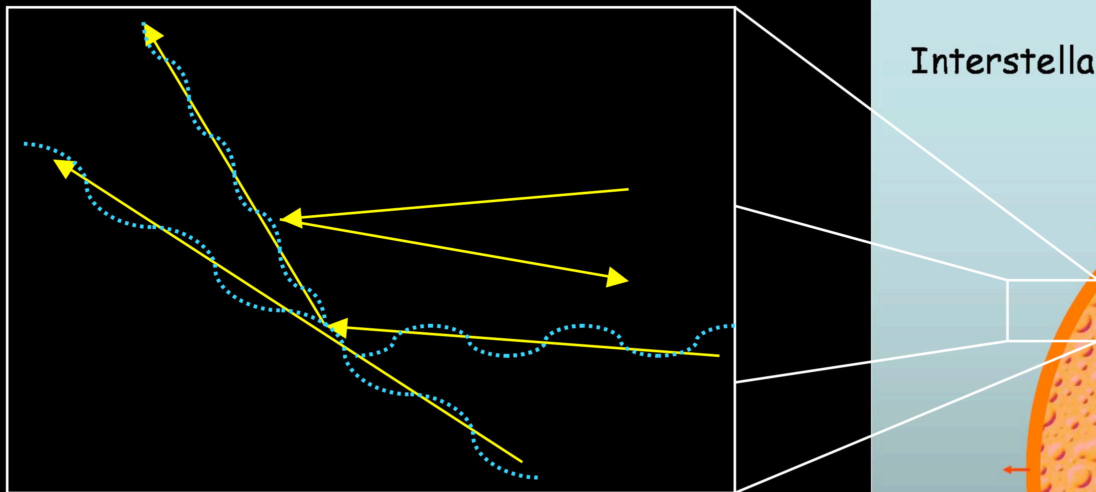

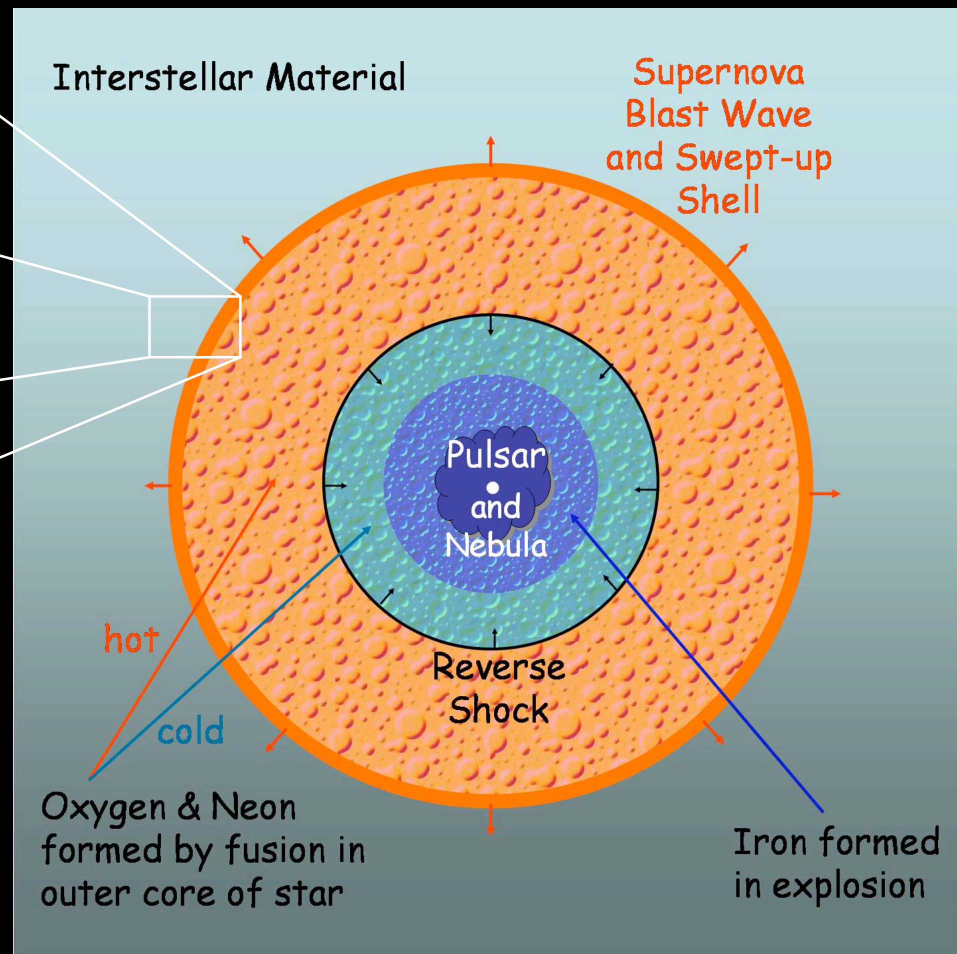

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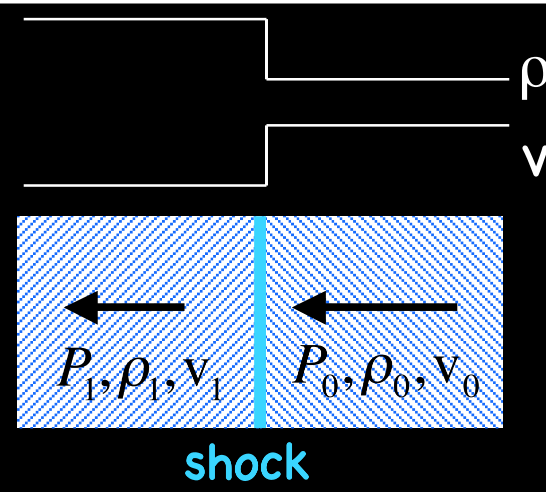
Shocks in SNRs

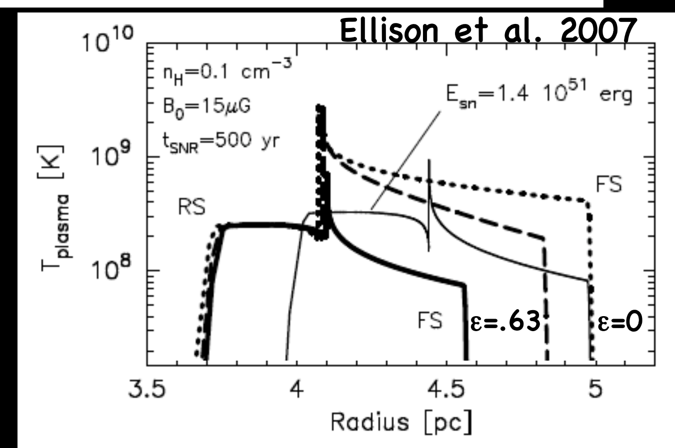


- Expanding blast wave moves supersonically through CSM/ISM; creates shock
  - mass, momentum, and energy conservation across shock give (with $\gamma=5/3$)

$$\rho_1 = \frac{\gamma+1}{\gamma-1}\rho_0 = 4\rho_0 \qquad v_1 = \frac{\gamma-1}{\gamma+1}v_0 = \frac{v_0}{4} \qquad T_1 = \frac{2(\gamma-1)}{(\gamma+1)^2}\frac{\mu}{k}m_H v_0^2 = 1.3\times10^7 v_{1000}^2 \text{ K}$$

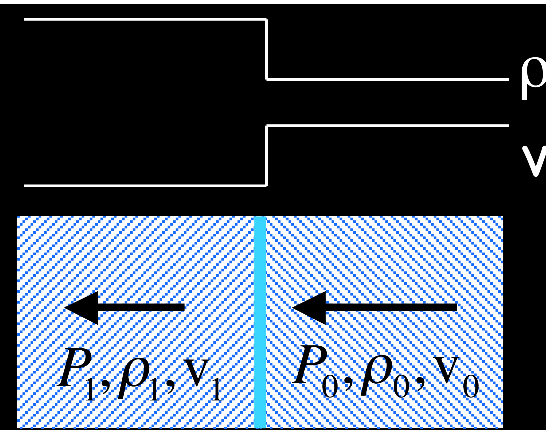
$$v_{ps} = \frac{3v_s}{4}$$

X-ray emitting temperatures



- Shock velocity gives temperature of gas
  - can get from X-rays (modulo NEI effects)
- If cosmic-ray pressure is present <u>the temperature will be lower than this</u>
  - radius of forward shock affected as well

Shocks in SNRs



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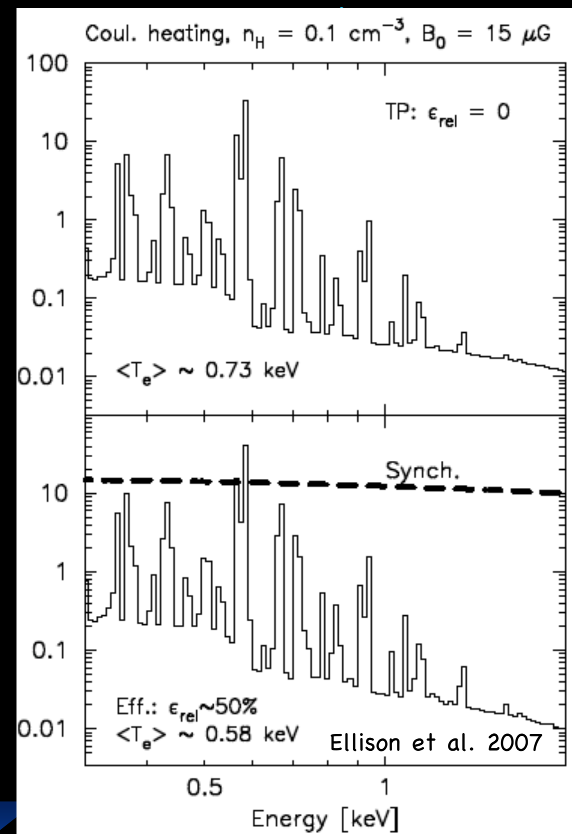

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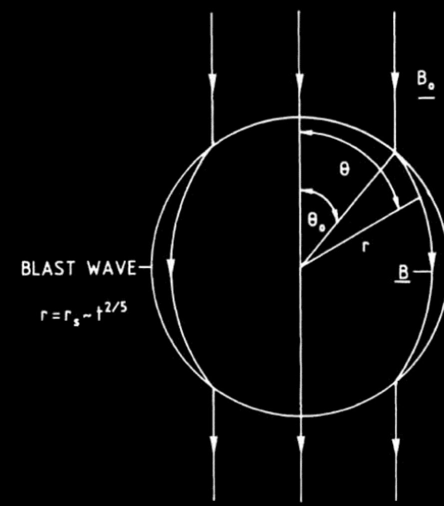
Particle Acceleration in SNRs

- Require quasi-parallel shock to set up turbulence from particles streaming upstream
  - the waves from the turbulence confine particles to shock region to provide further acceleration
  - only some regions of the SNR are likely to be efficient accelerators

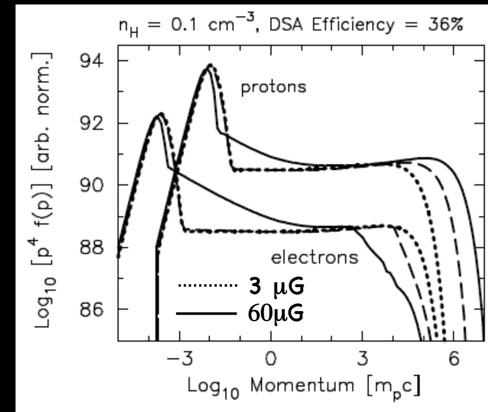


- Total efficiency in DSA can be very high (>50%)
  - no obvious problem coming up with significant contribution to CR spectrum

- Maximum energy limited by:
  - particle escape from shock
  - finite age of SNR (limit on total acceleration time)
  - synchrotron losses (for electrons)

- Radio and X-ray data appear to require strong B fields
  - curvature of radio spectrum; thickness of synchrotron filaments

Particle Acceleration in SNRs



- Require quasi-parallel shock to set up turbulence from particles streaming upstream
  - the waves from the turbulence confine energetic particles to shock region to provide further acceleration
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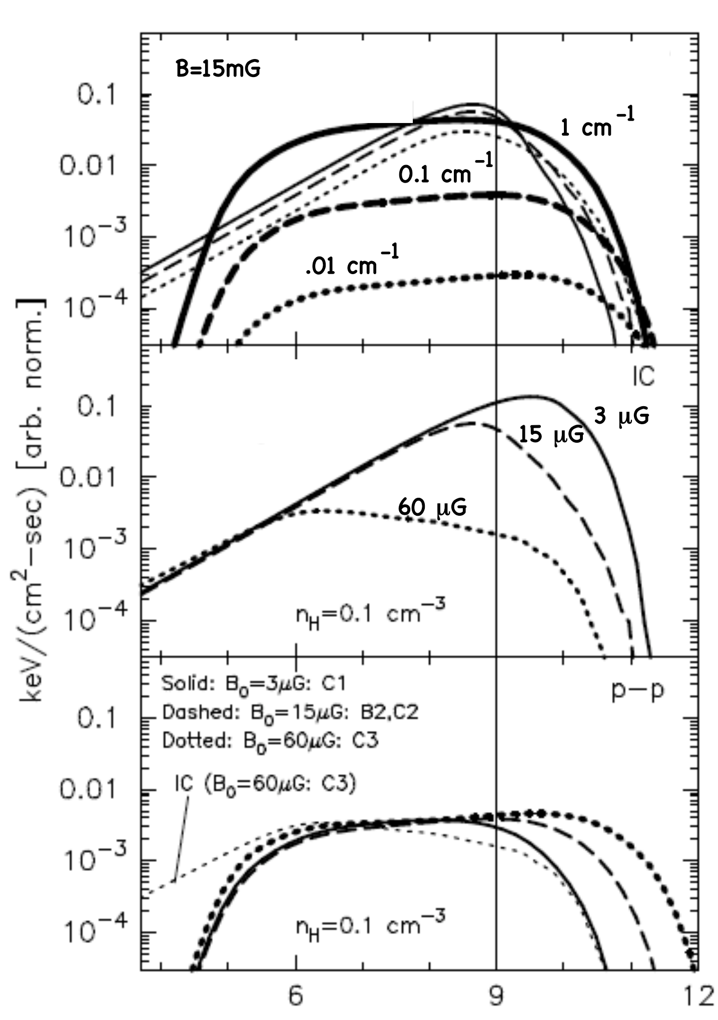
Electrons:
- large B lowers max energy due to synch. losses

Ions:
- small B lowers max energy due to inability to confine energetic particles

Current observations suggest high B fields

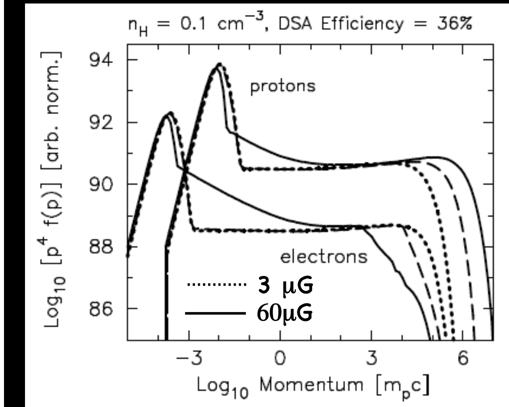
γ-ray Emission from SNRs

t=500y, ε=36%



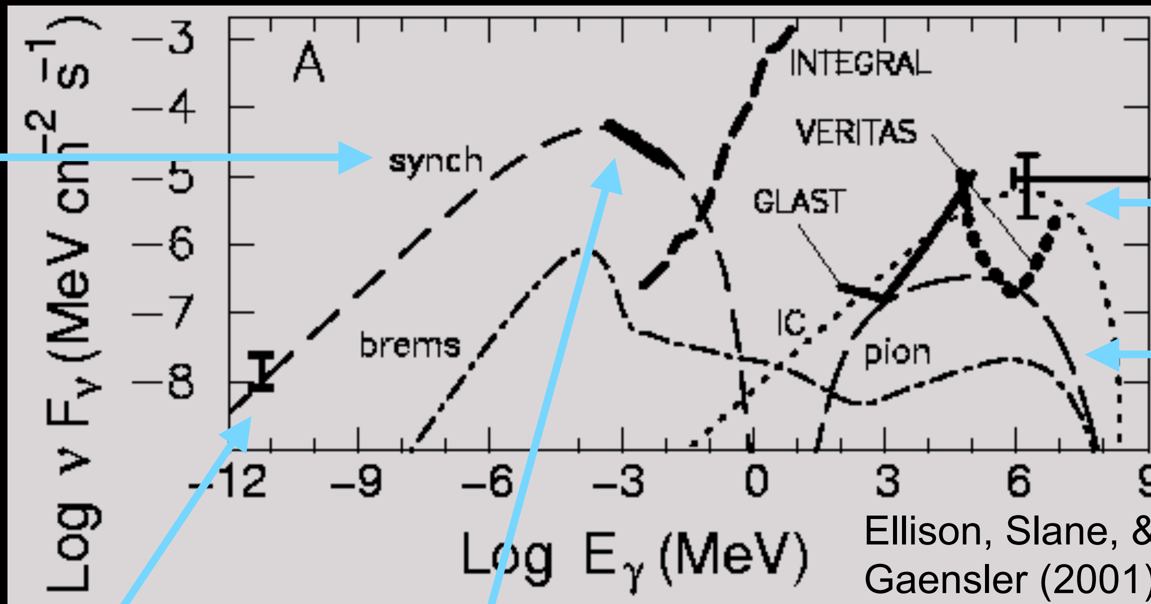
Ellison et al. 2007

- Neutral pion decay
  - ions accelerated by shock collide w/ ambient protons, producing pions in process: $\pi^0 \longrightarrow \gamma\gamma$
  - flux proportional to ambient density; SNR-cloud interactions particularly likely sites
- Inverse-Compton emission
  - energetic electrons upscatter ambient photons to γ-ray energies
  - CMB, plus local emission from dust and starlight, provide seed photons



- High B-field can flatten IC spectrum
  - also reduces IC flux relative to synchrotron
  - difficult to differentiate cases; VHE observations crucial

Broadband Emission from SNRs

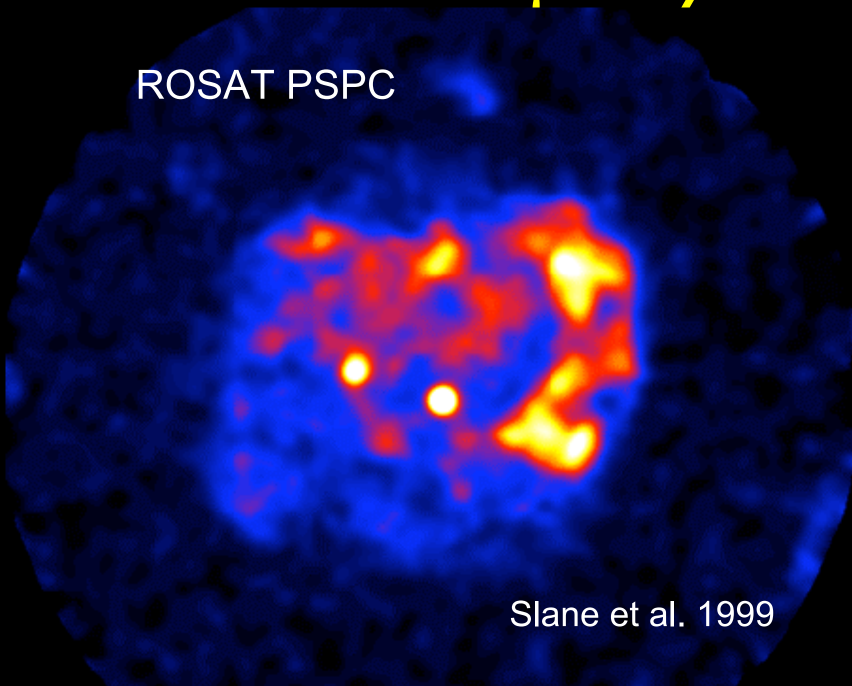


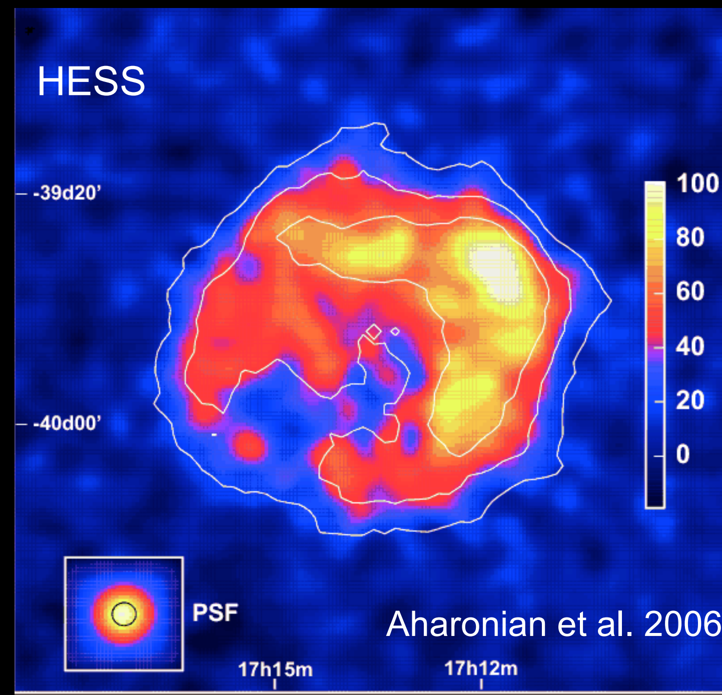
- synchrotron emission dominates spectrum from radio to x-rays
  - shock acceleration of electrons (and protons) to > 10^{13} eV

E_{max} set by age or energy losses
- observed as spectral turnover

- inverse-Compton scattering probes same electron population; need self-consistent model w/ synchrotron
- pion production depends on density
  - TeV observations required (as well as GLAST)

γ-rays from G347.3-0.5





- X-ray observations reveal a nonthermal spectrum everywhere in G347.3-0.5
  - evidence for cosmic-ray acceleration
  - based on X-ray synchrotron emission, infer electron energies of ~50 TeV

- This SNR is detected directly in TeV gamma-rays, by HESS
  - γ-ray morphology very similar to x-rays; suggests I-C emission
  - spectrum seems to suggest π^0-decay

WHAT IS EMISSION MECHANISM?

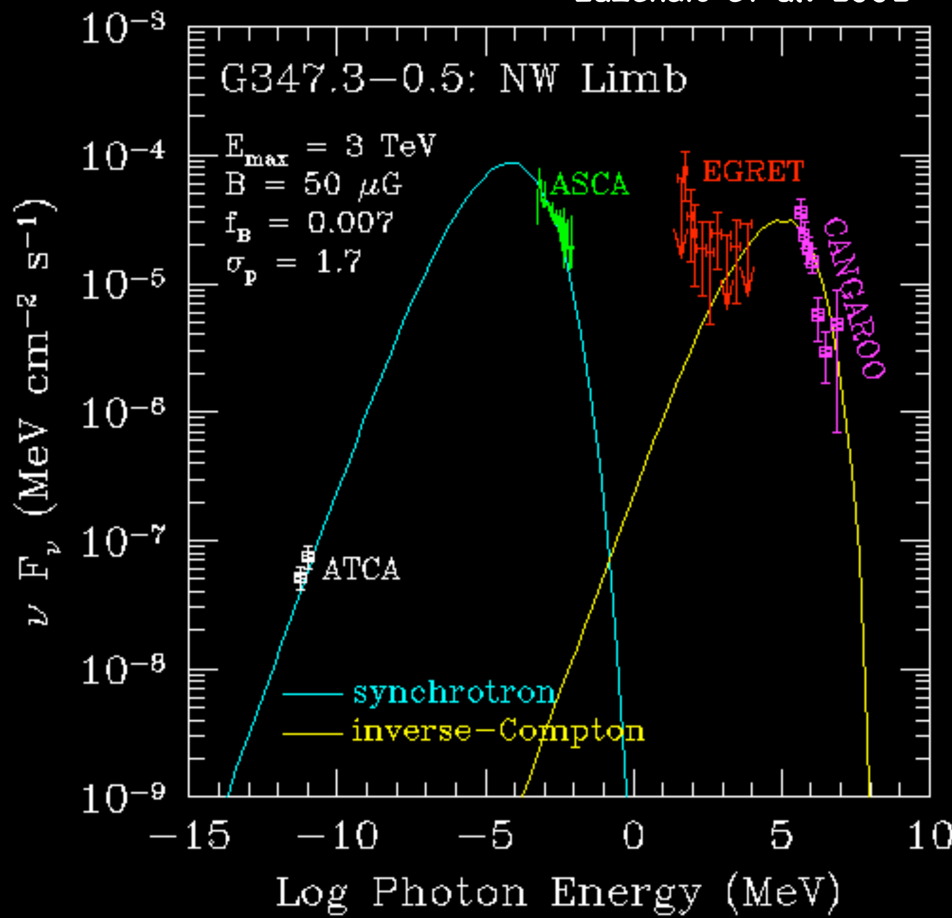
Modeling the Emission

- Joint analysis of radio, X-ray, and γ-ray data allow us to investigate the broad band spectrum
  - data can be accommodated along with EGRET upper limits, with no contributions from pion decay
  - large magnetic field is required, with relatively small filling factor

- However… HESS spectrum is completely inconsistent with that reported by CANGAROO
  - broader spectrum suggests pion origin, but implied densities appear in conflict with thermal X-ray upper limits

- BUT… strong magnetic field can flatten inverse-Compton spectrum
  - ORIGIN NOT YET CLEAR

Lazendic et al. 2002



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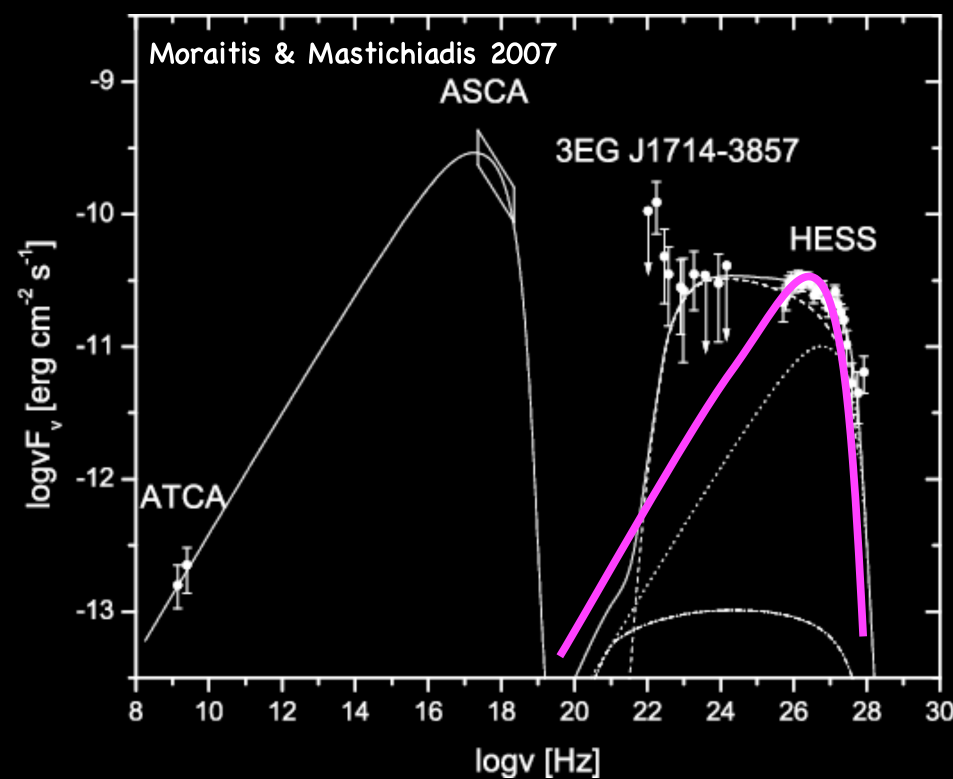
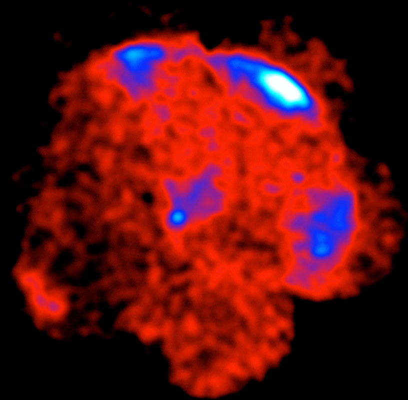
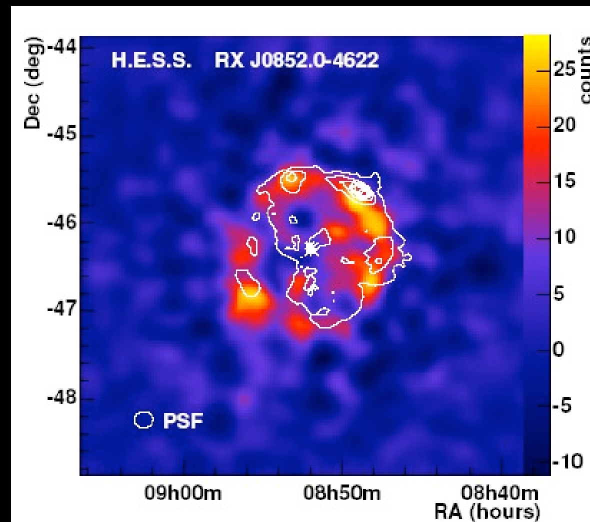


Other TeV SNR Examples

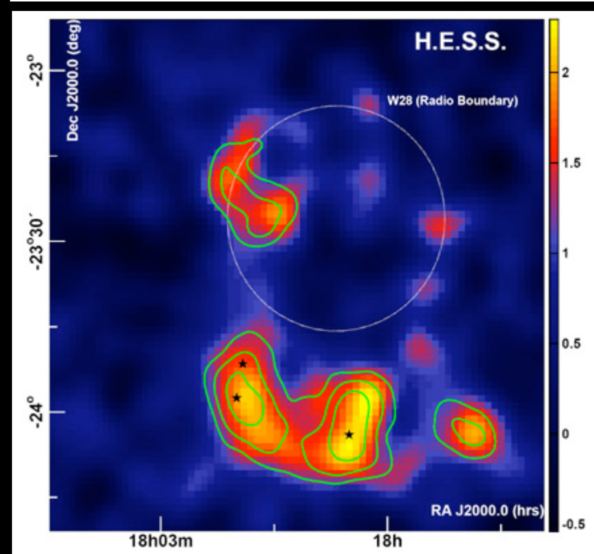
Vela Jr.





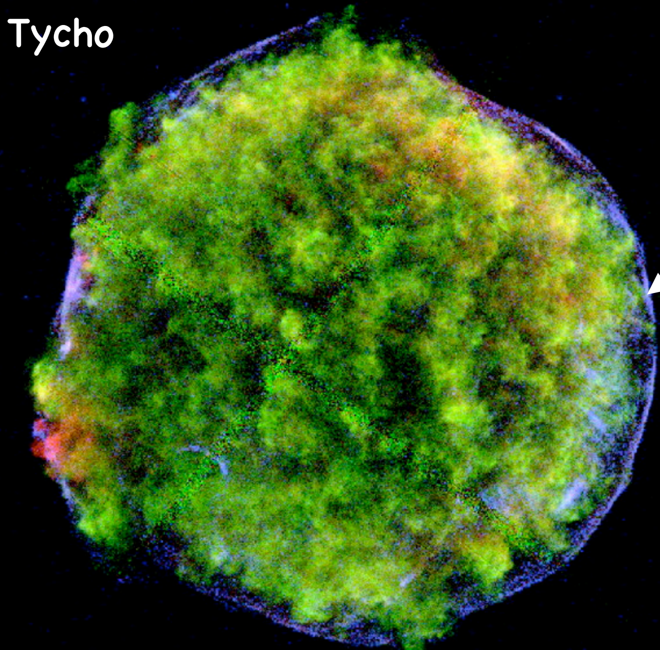
- Similar in appearance and flux to RX J1713
  - nearby and young
  - unclear whether spectrum is IC or pp

W28

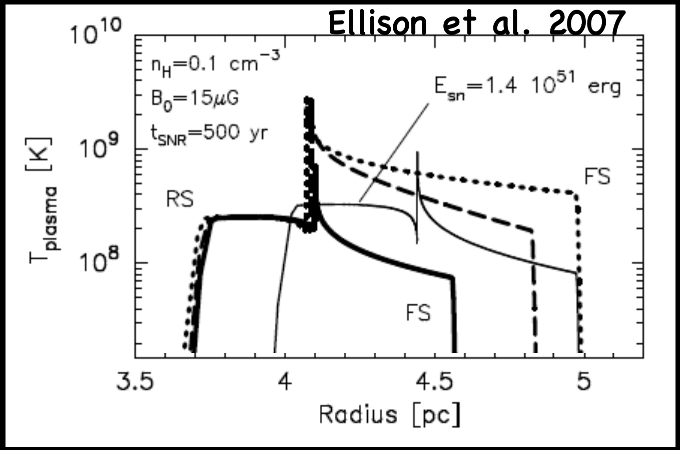


- Interaction with molecular cloud, or emission from the cloud?
  - emission also evident from nearby HII regions

Aside: Evidence for CR Ion Acceleration



Warren et al. 2005



- Efficient particle acceleration in SNRs affects dynamics of shock
  - for given age, FS is closer to CD and RS with efficient CR production
- This is observed in Tycho's SNR
  - "direct" evidence of CR ion acceleration

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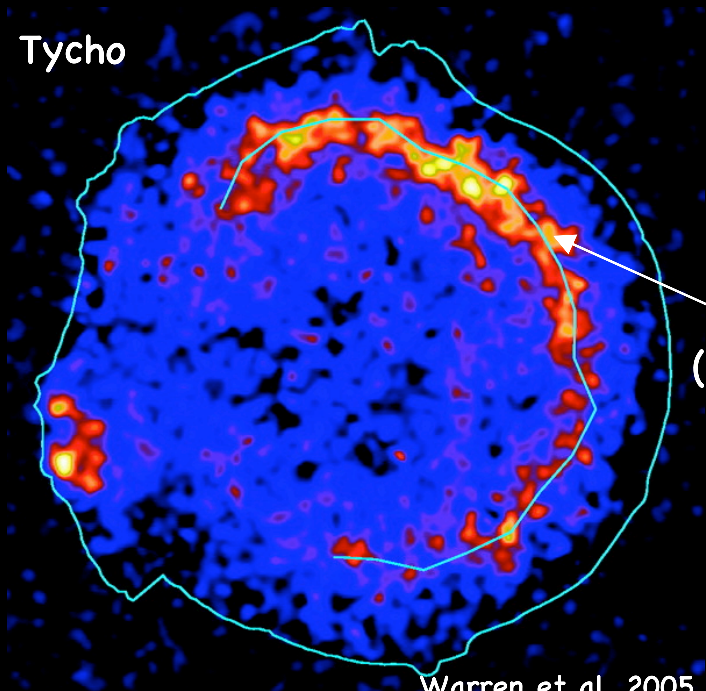

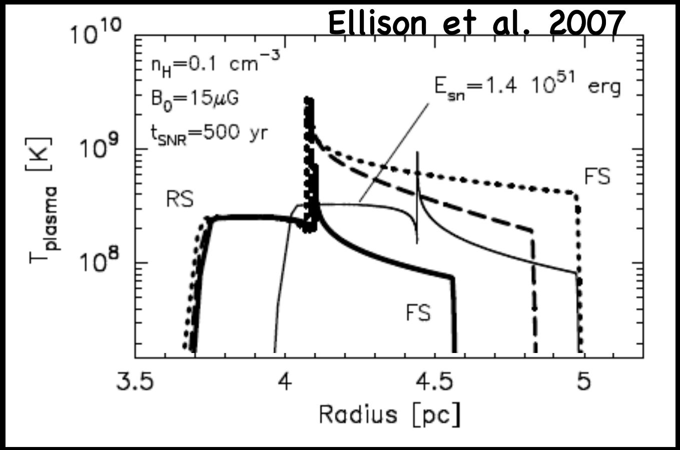

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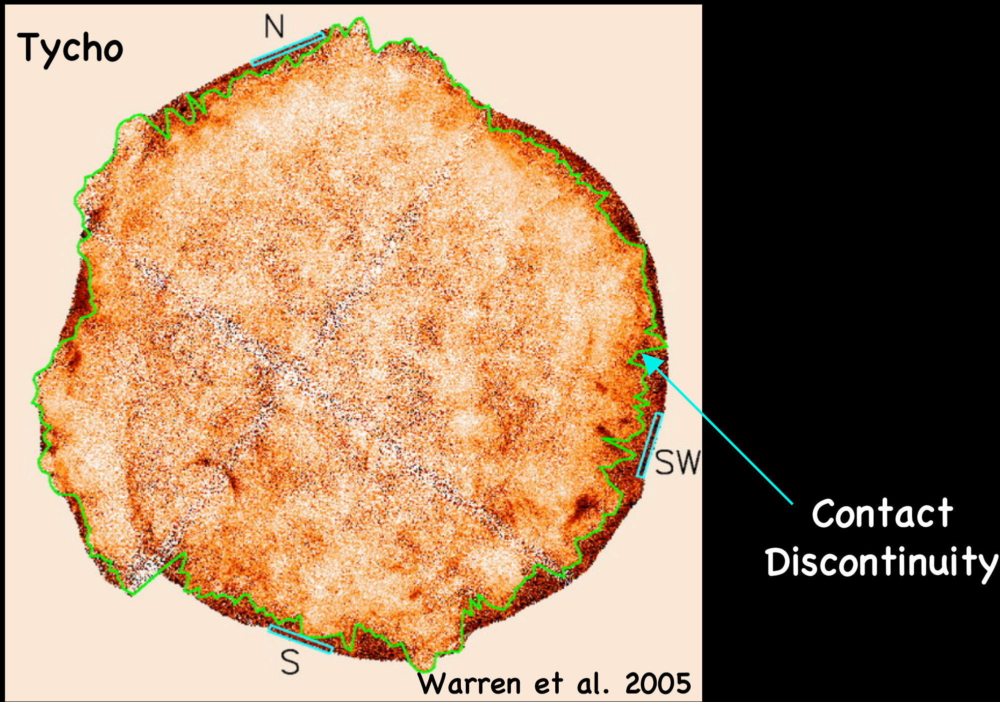

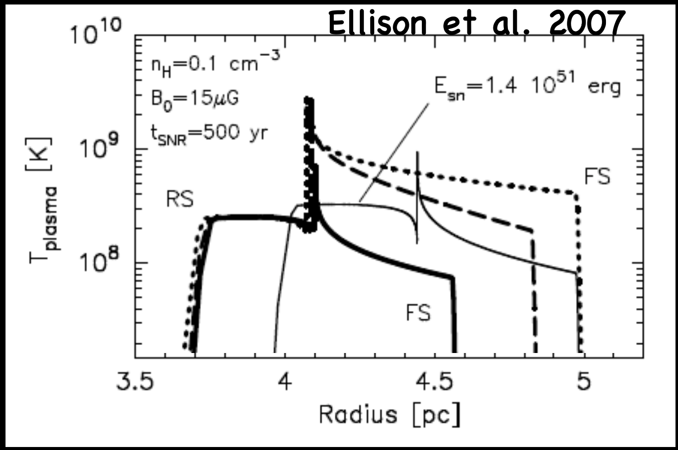

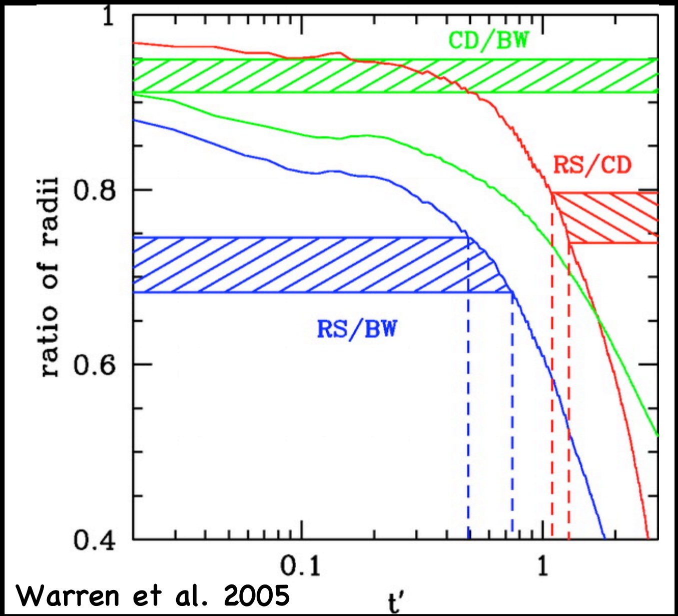

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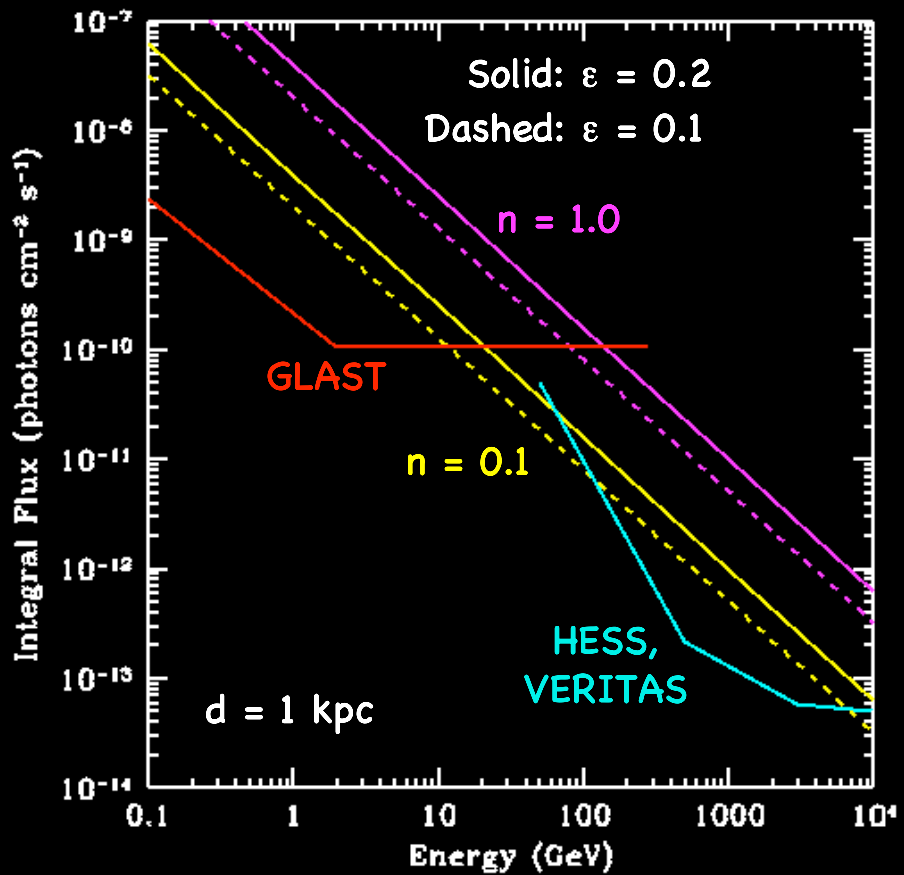
TeV Sensitivity for SNRs



- The expected $\pi^0 \longrightarrow \gamma\gamma$ flux for an SNR is

$$F(>E_{TeV}) \approx 5 \times 10^{-11} \varepsilon E_{51} d_{kpc}^{-2} n E_{TeV}^{1-\alpha} \text{ phot cm}^{-2} \text{ s}^{-1}$$

where ε is the efficiency, α is the spectral index of the particles, and n is the ambient density (Drury et al. 1994)
  - nearby SNRs should be strong TeV sources, particularly in regions of high density

- Efficient acceleration can result in higher values for I-C γ-rays
  - spectra in TeV band can constrain the emission mechanism
  - high sensitivity needed for distant SNR

(Note that efficiency can be >>0.1)

Why Do We Need Higher Sensitivity?

- Spectra
  - current spectra for brightest SNRs are not quite sufficient for determining nature of emission or clearly defining cut-offs
  - need to be able to determine this for these and fainter sources

- More sources:
  - the conditions for efficient particle acceleration aren't well-understood; we need a much larger sample of sources

- Detect old SNRs
  - a large fraction of the total energetic particle population accelerated by SNRs is produced late in their lives, when the remnants are very large
    => surface brightness is very low

Contributions from PWNe: MSH 15-52

- Unshocked wind from pulsar expected to have $\gamma = 10^6$
  - X-ray synchrotron emission requires $\gamma > 10^9$
  - acceleration at wind termination shock

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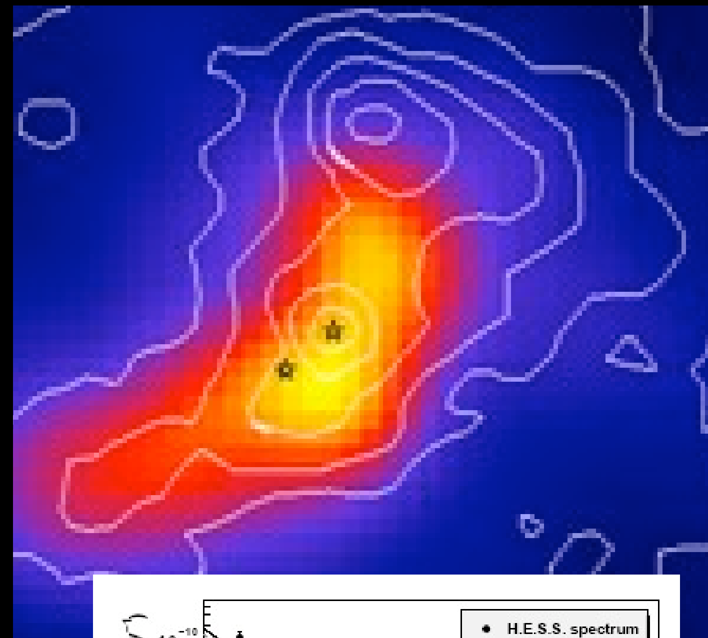
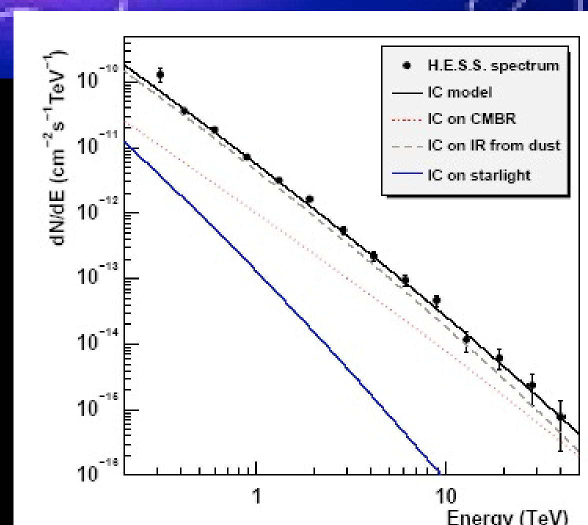
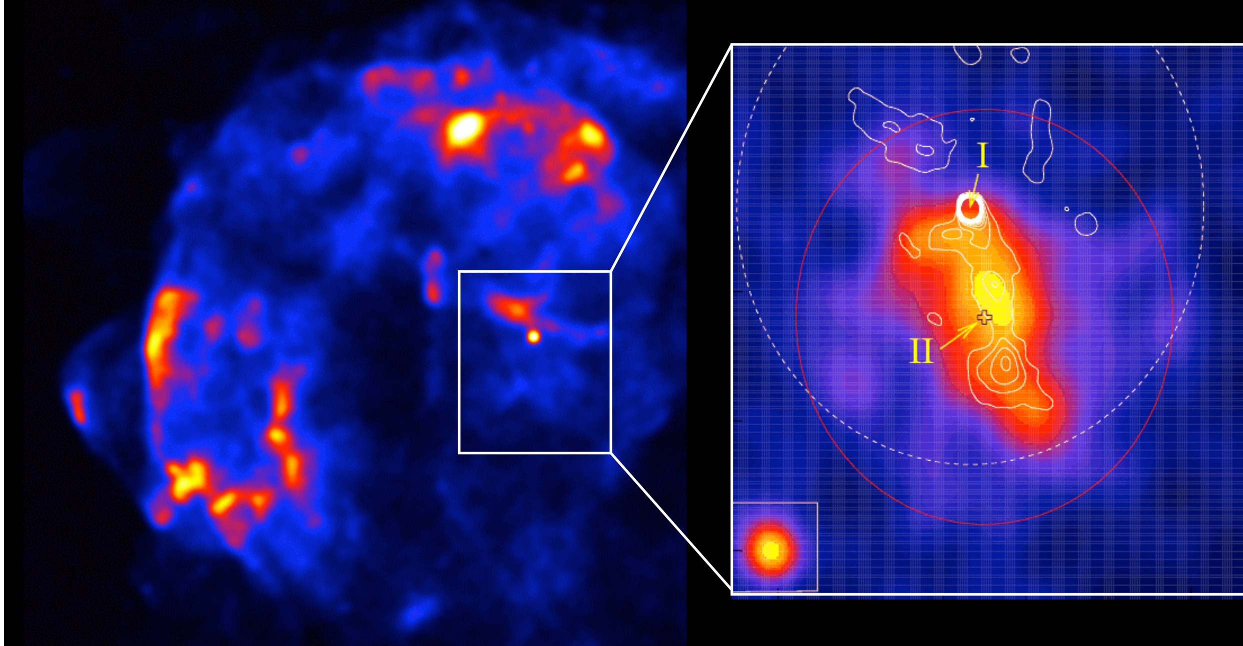
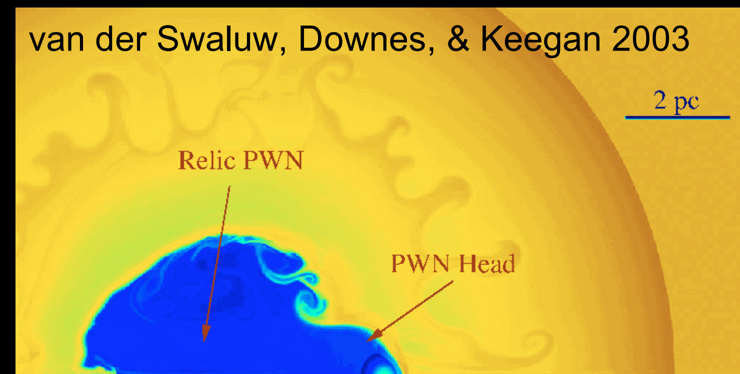
- HESS observations reveal extended jet that corresponds to X-ray structure
  - spectrum well-described by inverse-Compton emission dominated by local IR field from dust





Contributions from PWNe: Vela X





- Elongated hard X-ray structure extends southward of pulsar
  - clearly identified by HESS
  - this is not the pulsar jet (which is known to be directed to NW)
  - presumably relic nebula that has been disturbed by (asymmetric) passage of reverse shock
- Similar extended structures seen offset from field pulsars
  - deep TeV studies needed

Summary

- SNRs are efficient accelerators of cosmic ray electrons and ions
  - expect production of γ-rays from $\pi^0 \longrightarrow \gamma\gamma$ and I-C processes
  - current TeV sensitivity can detect brightest SNRs
  - spectra can provide crucial input for differentiating between emission mechanisms

- Radio/X-ray observations provide constraints on energetic particles, but extension to higher energies is crucial to understand maximum particle energies and accelaration mechanisms
  - higher TeV sensitivity is needed to better constrain current results and to reveal new sources

- TeV telescopes are already breaking new ground on PWN work
  - detection of jets holds promise for other PWNe
  - very large structures offset from pulsars may be identifying a large class of PWNe in post-RS interaction phase
  - higher angular resolution is of interest here